AZIMUTHALLY AVERAGED RADIAL $S_{100\mu M}/S_{60\mu M}$ DUST COLOR TEMPERATURES IN SPIRAL GALAXIES

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ABSTRACT The IRAS $S_{100\mu m}/S_{60\mu m}$ dust color temperature profiles are presented for two nearby spiral galaxies M 101 and M 81. The radial dust temperature profiles provide an important constraint on the origin of the far-infrared luminosity. The observed dust temperature is compared with that expected for diffuse interstellar dust heated by the general interstellar radiation field within each galaxy. The implications for the contribution of cirrus to the far-infrared luminosity of M 101 and M 81 are discussed.

INTRODUCTION

The IRAS HiRes images provide the unique opportunity to quantify the radial dependence of the dust color temperature in several nearby spiral galaxies of large angular size. The radial dependence of the $S_{100\mu m}/S_{60\mu m}$ dust color temperature, in particular, is important for constraining the origin of the far-infrared luminosity in spiral galaxies for two reasons. First, the bulk, ~ 80 %, of the far-infrared luminosity is radiated between 60 and 100 μm due to the fact that the far-infrared spectral energy distribution of spiral galaxies typically peaks at a wavelength of about $100\mu m$. Second, the radial dependence of the $S_{100\mu m}/S_{60\mu m}$ dust color temperature profile can, in some cases, distinguish between the two primary contending models for the origin of the far-infrared luminosity in spiral galaxies; the star formation model in which the far-infrared luminosity is dominated by the radiation from dust heated by O and B stars, and the cirrus model, in which the far-infrared luminosity is produced by diffuse dust heated by the general interstellar radiation field of non-ionizing stars.

At issue in the controversy surrounding the origin of the far-infrared luminosity is whether or not the far-infrared fluxes that were measured for literally thousands of galaxies by the Infrared Astronomical Satellite (IRAS) can be utilized to measure high mass star formation rates. Although use of the Hα emission line luminosity is a less controversial way to measure high mass star formation rates, the number of galaxies for which the Hα emission line luminosity has been measured is limited to about 200 galaxies at present (Kennicutt and Kent 1983; Bushouse 1987; Romanishin 1990). In contrast, IRAS measured far-infrared fluxes for literally thousands of galaxies. Consequently, the IRAS database is regarded as a potentially valuable resource for quantifying high mass star formation rates (Young et al. 1986; Helou et al. 1985; Gavazzi et al. 1986; Leech et al. 1988; Devereux and Young 1990; 1991, 1992).

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Evidence supporting high mass stars as the origin of the far-infrared luminosity includes the fact that the O and B stars, which are required to generate the Hα emission line radiation in galaxies, can also supply the luminosities measured in the far-infrared, independent of the $S_{100\mu m}/S_{60\mu m}$ dust color temperature (Devereux and Young 1990) and spiral type (Devereux and Young 1991). Nevertheless, the ambiguity surrounding the origin of the far-infrared luminosity in spiral galaxies remains due to the perception that 70 - 90 % of the far-infrared luminosity may be produced by cirrus, or more specifically, diffuse interstellar dust heated by the radiation field of non-ionizing stars (Walterbos and Schwering 1987; Lonsdale-Persson and Helou 1987; Bothun, Lonsdale and Rice 1989).

We know that the general interstellar radiation field can, in principle, supply the luminosities measured in the far-infrared because it requires only a moderate amount of extinction of the optical light, corresponding to $A_v = 0.5$ - 1.0 magnitudes, to account for the L_{fir}/L_{blue} luminosity ratios observed for spiral galaxies. What may be more difficult to explain are the warm dust temperatures indicated by the $S_{100\mu m}/S_{60\mu m}$ ratio. The purpose of this contribution is to show how the radial dependence of the $S_{100\mu m}/S_{60\mu m}$ dust color temperature can provide an important constraint on the origin of the far-infrared luminosity within spiral galaxies.

Since the angular resolution of the HiRes 100 μm images is about 100″ and lower than the ~ 60″ resolution of the HiRes 60 μm images, it is necessary, for the purposes of calculating dust color temperatures, to convolve the 60 and 100 μm HiRes images to the same resolution. The following procedure was adopted:

1. Display the beam resolution maps in order to determine the half power beam size and shape at 60 and 100 μm.

2. By trial and error, determine the kernels necessary to convolve the 60 and 100 μm beam profiles to the same resolution. With a little practice it is usually possible to achieve circular beams with a full width half maximum size of 105″ at both 60 and 100 μm.

3. Perform the same convolutions on the HiRes 60 and 100 μm galaxy images.

4. Measure the 60 and 100 μm galaxy fluxes at a resolution that is no higher than the resolution of the convolved beams. Generate azimuthally averaged radial dust temperature profiles by taking the ratio of the 60 and 100 μm fluxes measured within elliptical annulae. The major axis of the ellipse, r, is aligned with the major axis of the galaxy and the minor axis width of the ellipse is r cos (i), where i is the galaxy inclination.

5. Quantify the uncertainty in each of the annular fluxes by measuring the noise (Jy/sr) at several background locations well away from the galaxy. This is possible using only HiRes images that have been processed with the *fbias* option which preserves the noise inherent in the original data. Determine the average noise (Jy/sr) and multiply the noise by the solid angle of each annulus within which the fluxes were measured. Propagate the uncertainties to determine the error in the $S_{100\mu m}/S_{60\mu m}$ flux ratio at each radius.

6. Convert the $S_{100\mu m}/S_{60\mu m}$ flux ratios into dust color temperatures in order to facilitate comparison with models.

RESULTS

The azimuthally averaged $S_{100\mu m}/S_{60\mu m}$ radial dust color temperature profiles are illustrated in Figure 1 for the nearby spiral galaxies M 101 and M 81. The dashed lines in Figure 1 represent the temperatures expected for dust grains of a variety of sizes and compositions when heated by the general interstellar radiation field. The intensity of the general interstellar radiation field was determined from the extinction corrected visual surface brightness profile for each galaxy. The dashed line labelled cirrus indicates the temperature expected for a dust grain size distribution that is required to explain IRAS measurements of Galactic cirrus (Low et al. 1984). The temperatures are based on the models of Desert, Boulanger and Puget (1990) who calculated the $S_{100\mu m}/S_{60\mu m}$ flux ratios expected for a cirrus grain size distribution that is irradiated by stellar radiation fields ranging in intensity from 0.3 to 1000 times that in the solar neighborhood. A visual surface brightness of 23.2 mag/(arc sec)^2 was adopted for the solar neighborhood. The $S_{100\mu m}/S_{60\mu m}$ flux ratios are converted into dust temperatures assuming a λ^{-1} emissivity law, although qualitatively, the results described below remain unchanged if a λ^{-2} emissivity law were used instead. The dust temperatures expected for large, $\geq 0.1\mu m$, Si and C grains are based on the models of Jura (1982).

M 101

M 101 is a late type (SABcd) spiral galaxy. The radial $S_{100\mu m}/S_{60\mu m}$ dust color temperature profile is remarkably uniform. The mean dust temperature is 31 $\pm$ 2 K for a λ^{-1} emissivity law (see Figure 1a). The observed dust temperature is well in excess of the temperature expected for large, $\geq 0.1\mu m$, dust grains heated by the general interstellar radiation field. The observed dust temperature is also higher than expected for cirrus. Evidently the general interstellar radiation field is unable to heat cirrus up to the high temperature that is observed for the dust in M 101. The surface brightness of M 101 would, in fact, have to be at least 1.5 magnitudes brighter in the V band in order for the general interstellar radiation field to be able to heat the cirrus up to the observed temperature.

M 81

M 81 is an early type (SAab) spiral galaxy. The radial $S_{100\mu m}/S_{60\mu m}$ dust color temperature profile varies with radius from a peak value of about 35 K (λ^{-1}) in the nucleus to about 28 K (λ^{-1}) in the disk (see Figure 1b). The observed dust temperature is well in excess of the temperature expected for large, $\geq 0.1\mu m$, dust grains heated by the general interstellar radiation field. On the other hand, the observed dust temperature appears to be consistent with that expected for diffuse interstellar dust, or equivalently cirrus, that is heated by the general interstellar radiation field within M 81.

DISCUSSION

The results presented for M 101 and M 81 highlight the importance of the radial dust temperature profiles in constraining the origin of the far-infrared luminosity within spiral galaxies. In the case of the late type spiral galaxy

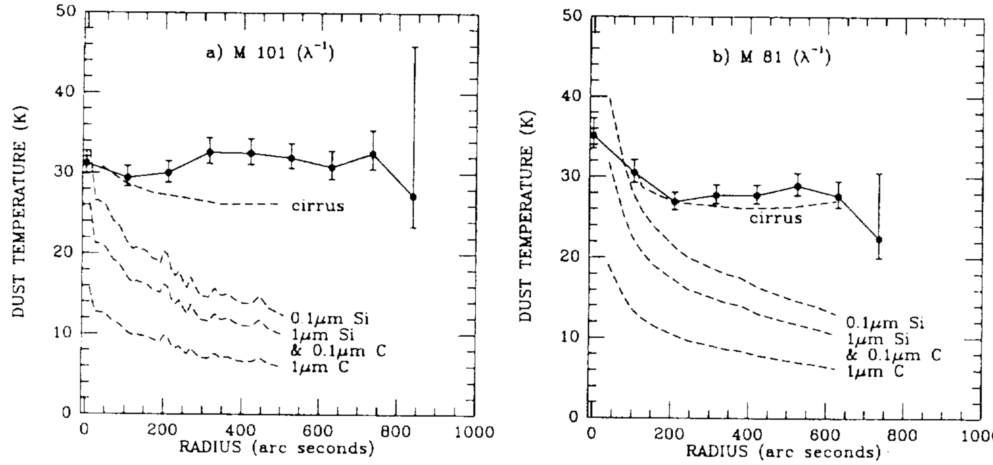

FIGURE 1 The solid lines indicate the azimuthally averaged $S_{100\mu m}/S_{60\mu m}$ dust color temperature profiles observed for the nearby spiral galaxies M 101 (left panel) and M 81 (right panel). The dashed lines indicate the temperatures expected for dust grains of a variety of sizes and compositions when heated by the general interstellar radiation field within each galaxy.

M 101, an explanation of the origin of the far-infrared luminosity in terms of cirrus, or more specifically, diffuse interstellar dust heated by the radiation field of non-ionizing stars, is untenable because the intensity of the general interstellar radiation field is too low, by at least 1.5 magnitudes, to heat the dust up to the observed temperatures. The limit is necessarily a lower limit because of the inevitable contribution of ionizing stars to the V band surface brightness profile that was used to estimate the intensity of the non-ionizing interstellar radiation field within M 101. On the other hand, O and B stars do provide a viable alternative explanation for the origin of the far-infrared luminosity because the dust temperature is comparable to that observed for Galactic and extragalactic HII regions (Scoville and Good 1989; Sodroski et al. 1989; Rice et al. 1990) at all locations within M 101.

In the case of the early-type spiral galaxy M 81, the far-infrared luminosity may be attributed to diffuse dust heated by the general interstellar radiation field, because the expected temperature is very similar to the temperature that is actually observed. The distinction between ionizing and non-ionizing stars as the origin of the far-infrared luminosity would, however, require a further determination of the relative contribution of ionizing and non-ionizing stars to the general interstellar radiation field within M 81.

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